Plantar pressure cartography reconstruction from 3 sensors

Hussein Abou Ghaida, Serge Mottet and Jean-Marc Goujon

Abstract—**Foot problem diagnosis is often made by using pressure mapping systems, unfortunately located and used in the laboratories. In the context of e-health and telemedicine for home monitoring of patients having foot problems, our focus is to present an acceptable system for daily use.**

We developed an ambulatory instrumented insole using 3 pressures sensors to visualize plantar pressure cartographies. We show that a standard insole with fixed sensor position could be used for different foot sizes. The results show an average error measured at each pixel of 0.01 daN, with a standard deviation of 0.005 daN.

I. Introduction

Plantar pressure measurements are used in the diagnostics of foot related problems such as plantar foot pain due to diabetics, age or joint disease [1-3]. In the quiet standing position or during walking, plantar pressures highlight the compression of the soft tissues (skin, fat, ligaments, and muscles) under the feet. The plantar pressure distribution can be measured by using insoles made of a pressure sensor matrix. The F-Scan® mobile System [4] with 954 sensors or Pedar® with 256 sensors [5] are the most popular instrumented insole systems used by podiatrists [6-8].

Those systems are mobile but not convenient for ambulatory applications. These insoles can be used for a limited number of measurements. The batteries offer a maximum of 2 hours of autonomy during measurement.

On the other hand, simplified sensors system have been proposed, with 3 to 10 pressure sensors per foot, but without providing realistic and suitable plantar maps[9-11].

A fully ambulatory system can be imagined, based on a sensor network with low power consumption and wireless transmission. The number of data to be processed and stored should be small and adapted to a real time processing. The idea is to integrate the data treatment into an embedded system.

We propose an instrumented insole system with 3 pressure sensors per foot, which offers podiatrists and patients real time plantar pressure maps. The numerical method, which generates the pressure maps from the data of 3 sensors per foot, requires a learning phase. The mathematical model depends on the foot properties of each subject. For this, a biomechanical model of the foot properties is proposed and is applied to the plantar pressure map calculation.

Firstly, we describe the pressure sensor system. Then the learning method developed to identify the parameters of the transfer functions used in the numerical methods is detailed.

II. Material

A. Sensors

The sensors used for the experiment are of Force Sensing Resistors type. These sensors are simple to use, low cost (less than 1$) and flexible. The sensor voltage response exhibits an exponential behavior (1):

$$V(F) = a_1 \cdot (1 - \exp(-a_2 \cdot F)) + a_3 \tag{1}$$

The sensor voltage is amplified before analog to digital conversion. The amplified signal of each sensor may differ, due to the characteristic spread of the components and the amplification electronics. The responses of the amplified sensor voltages have been calibrated by applying forces between 0 and 50 daN. The identification of the 3 parameters a_i is made for each sensor. A numerical filter is used to remove the high frequency noise due to high resistance of the sensor, the cable length and the electronic circuit power supply.

The sensors are fixed under a commercially available leather shoe insole (less than 3$). Those insoles prevent moisture in classical shoes but other thin materials could be used. The thickness is 2 mm including the black elastomer under layer, as shown in Figure 1 A. To fit the shoe size, the insoles can be reduced by cutting along the printed foot size dotted lines, which is the case of the F-Scan insoles, Figure 1 C. The leather insole is then set on the F-Scan one, as shown in figure 1 B.

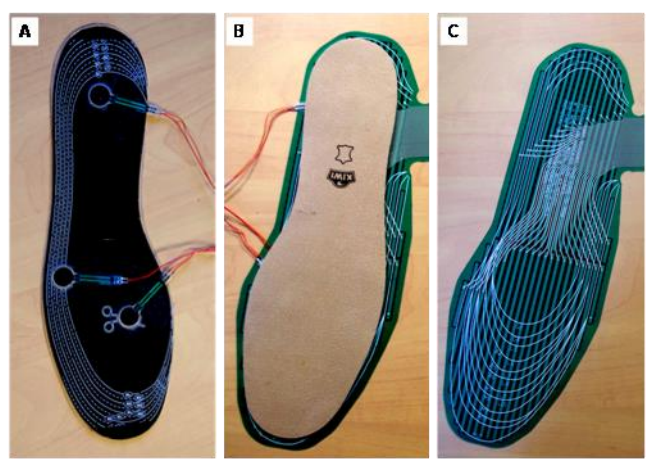

Figure 1: A) Bottom view of the leather insole with the sensors. B) Top view of the leather insole placed on a F-Scan insole. C) View of the F-Scan insole with its 950 sensors.

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B. Plantar pressure measurement

We use the F-Scan system as a reference for the pressure maps under the feet. The first step consists of measuring simultaneously the pressure distributions and the sensor responses for different postures. This step is performed to record the data necessary to identify the foot properties used in the numerical methods to extrapolate the plantar pressure maps from the 3 sensors. Moreover, this step allows the comparison between the results measured by the F-Scan system and 3 sensors system.

The plantar pressure cartographies are recorded by using the F-Scan® system (from Tekscan ®). The voltage delivered by the pressure sensors are recorded by using analog to digital converter from National Instrument interfaced by Lab View®. Both systems are externally trigged at the frequency of 20 Hz.

The posture has to vary during recording so that it can be used as a data base for the numerical methods. This variation is natural during walking, but, in standing position, the subject is asked to exaggerate his posture in mediolateral and anteroposterior directions in order to get enough displacement amplitude to calibrate the sensors.

III. Method

A. Foot model and hypothesis

In the standing position, equilibrium is controlled by the muscle action, which moves the distribution of the plantar pressure by changing the rotation of the foot around the ankle (anterior-posterior) and the repartition of the total weight of the body on both feet (lateral).

The force applied to the ankle compresses the foot, which can be considered essentially as a skeleton covered by an elastic medium made of soft tissues. The compression naturally increases plantar pressure.

One can consider that the foot skeleton can be divided into three parts, from back to front: the heel, the metatarsus and the phalanges. The soft tissues constitute a complex medium. The thickness and elasticity of the soft tissues depend on their location under the foot, but the heel and the metatarsal heads support the biggest pressure.

A simplified model has been developed in order to describe the relationship between posture and plantar pressure through mechanical foot characteristics.

Firstly, we consider the case of a bare foot on flat ground.

In order to describe the relationship between the force applied to the ankle and the plantar pressure distribution, we can define three elements for the mathematical model: FS, the foot seat, IS, the internal foot shape, and EM, the elastic medium. The parameters of each element are foot dependent.

B. Foot seat

The origin of the internal coordinates of the foot is the ankle, x being the lateral coordinate axis, y the longitudinal one (heel to forefoot) and z the vertical one.

The location of the foot in space is given by the vertical position of the ankle and the rotations around the ankle, as shown in Figure 2. The equation of the foot seat plan, is (2):

$$z_{FS}(x,y) = \tan(\alpha)\cdot x + \tan(\beta)\cdot y + c = a\cdot x + b\cdot y + c \quad (2)$$

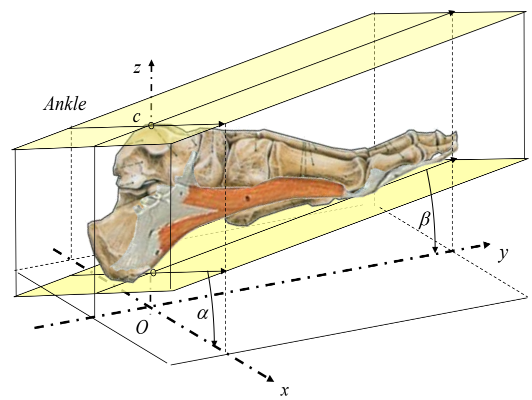

Figure 2: Illustration of the foot seat.

C. Internal foot Shape

The Internal foot Shape IS is a surface profile describing the non-compressive material mainly due to the skeleton. The internal foot shape is described by the distance of each foot point to the foot seat plan. Since the rotation angles are small, the component, $z_{IS}(x,y)$, along the z axis is not affected by the cosines of the angle set.

The foot shape is similar to a 3D profile of the underfoot, such as the one provided by a 3D scanner. The internal foot shape consists in the foot skeleton (Figure 3 A) covered by the other rigid media, such as the ligaments and the muscles, as shown in Figure 3 B.

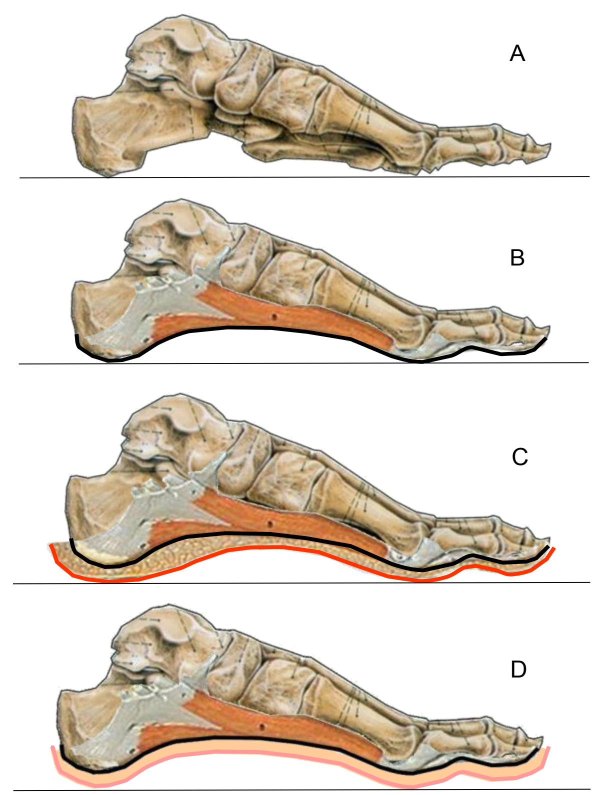

Figure 3: Foot model. A) Foot skeleton [12]. B) Internal foot shape. Elastic medium: C) in red, soft tissues, D) in pink, modelled elastic medium.

D. Elastic Medium

The internal foot shape (skeleton and rigid medium) is covered by soft tissues as shown in Figure 3 C. The thickness and the elasticity of the soft tissues depends on the underfoot location. The compression of the tissues induces a pressure.

To simplify the model, it is assumed that the soft tissues can be approximated by an equivalent uniform elastic medium EM. The elastic medium is uniform in terms of thickness and elastic properties (Figure 3 D).

The EM, elastic medium, compression as a function of the force has an exponential behavior (3):

$$z_c = thick \cdot \left(1 - \exp\left(-\frac{F}{stiff}\right)\right) \tag{3}$$

where z_c (mm) is the compression of the EM, $thick$ (mm) the thickness, $stiff$ (daN) the stiffness, and F (daN) the force applied on the surface of a pixel or a sensor.

The vertical compression z_c of the EM is directly related to the foot seat and the internal foot shape functions. If there is contact with the ground, $z_C(x,y) \geq 0$, then $z_C(x,y) = z_{FS}(x,y) + z_{IS}(x,y)$. The main relation (4) is then:

$$thick \cdot \left(1 - \exp\left(-\frac{F}{stiff}\right)\right) = a \cdot x + b \cdot y + c + z_{IS}(x,y) \tag{4}$$

The unknown parameter stiff is determined together with the internal foot shape $z_{IS}(x,y)$ for a fixed $thick$ value. For each posture, the foot seat is described by *a*, *b* and *c*.

IV. Results

A. Internal foot shape identification

The pressure maps are made with F-Scan, at a frequency of 20 frames/second during 30 seconds. Pressure maps for different foot seats are obtained. The number of measurements is large enough to extract the two foot seats for each time step, the two internal foot shapes and the effective stiffness of the elastic medium. Simultaneously the stiffness value for the sensors is determined (the stiffness depends on the surface of the sensor). The numerical method has been developed with MATLAB software on an ordinary desktop personal computer. The total computing time is about 10 seconds to identify the stiffness of the elastic medium and compute the internal foot shapes.

In the following, we present the results of the plantar pressure maps, for a 70 kg male subject with a foot length of 26 cm, bare-footed, in a standing position.

The thickness of the elastic medium is 5 mm. The calculated internal foot shape is shown in Figure 4. The height varies between 1 and 4.5 mm. A variation of 2 mm can be observed between the mid-foot and the forefoot or the heel. The variance study leads to an error of a few percent.

For each posture, the foot seat is determined from the responses of the three sensors. Using the foot seat, the calculated foot shape and the stiffness of the elastic medium the pressure maps are then simulated in real time.

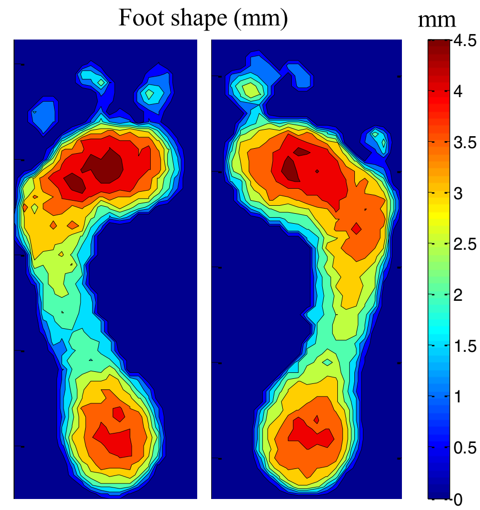

Figure 4: Internal foot shape altitude in mm.

B. Plantar pressure extrapolation

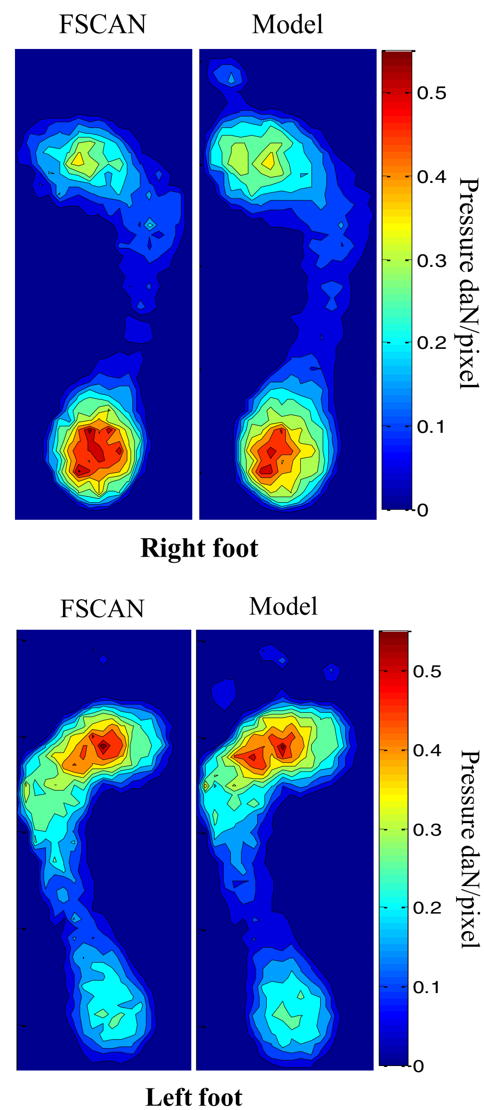

Figure 5: Left and right foot plantar pressure maps measured by F-Scan and extrapolated from 3 pressure sensors (Model).

We now compare the simulated maps to the measured F-Scan pressure maps. Figure 5 shows the plantar pressure measured for one of the standing positions. It can be seen that the extrapolated plantar pressure from the model highlights the anatomically support zones under the foot, such as the heel and the forefoot.

We can notice that the peak pressure value under the heel for the left and right foot is about 0.45 daN/(pixel area) for both measured and extrapolated pressures. The pressure under the toes does not appear in this position.

The average error measured at each pixel is 0.01 daN, with a standard deviation of 0.005 daN. This model therefore offers good prediction characteristics.

A comparison between measured and simulated plantar pressure maps have also been made during walking.

V. Discussion

A set of three sensors per foot, located at the heel, the first and the fifth metatarsus are fixed under a leather insole. These sensors permit the real time extrapolation of the plantar pressure map with low power consumption.

Different patients, whose foot sizes vary between 37 and 46 (European size), have been tested without changing the position of the sensors on the insoles. The white lines in figure 1A show the different locations of the foot as function of the foot size. The forefoot sensors are always located under the first and fifth metatarsus for smaller size. Changing the size of the foot changes mainly the heel position with regard to the corresponding sensor. We show that a standard insole with fixed sensors position could then be used for different foot sizes. Size adjustment to the shoe is simply made by cutting along the corresponding size line.

Thanks to the model of foot developed in this study, the plantar pressure maps are calculated from the measures of 3 pressure sensors per foot. The average difference on the force map per pixel, compared to F-Scan one is 0.01 daN, for a pressure variation between 0 and 0.5 daN/Pixel.

These results confirm the validity of the approximation of a uniform elastic medium in place of heterogeneous soft tissues. This assumption minimizes the complexity of the plantar soft tissue modeling.

For simplicity, the model assumes that the internal foot shape remains rigid when changing the seat. But the toe phalanges are articulated to the metatarsus and may move independently from the foot seat. Thus, some errors may occur when calculating the toe pressures, but they remain small compared to heel or forefoot pressures.

VI. Conclusion

We have proposed a new model of the foot based on simplified anatomical description. It provides a practical tool to simulate the plantar pressure distribution for podiatrists. Based on this foot model, the plantar pressure distribution can be obtained using only 3 pressure sensors per foot. For this, the internal foot shape is first calculated from plantar pressure cartographies, issued from the usual matrix systems, such as F-Scan or Pedar, avoiding the use of expensive equipment.

The sensors are to be used in a portable ambulatory monitoring system, with low power consumption and wireless transmission. This reduced number of data would be transmitted to podiatrist, or locally processed within a smart phone processor. Plantar pressure maps simulations are processed in real time.

This system could be suitable for studies of balance in the elderly or ulcer formation prevention in the feet of diabetics. These applications will be presented elsewhere. In the future, this model could be further developed to extrapolate the action of added insoles on the underfoot pressure when assigning thickness and stiffness to each area of the elastic medium. It could be an insole design tool for diabetic patients.

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